Production of cereals in northern marginal areas: An integrated assessment of climate change impacts at the farm level

Tuomo Purola[a,*], Heikki Lehtonen[a], Xing Liu[a], Fulu Tao[b], Taru Palosuo[c]

[a] Luke Natural Resources Institute Finland, Economics and Society, Latokartanonkaari 9, FI-00790 Helsinki, Finland
[b] Luke Natural Resources Institute Finland, Management and Production of Renewable Resources, Humppilantie 14, FI-31600 Helsinki, Finland
[c] Luke Natural Resources Institute Finland, Management and Production of Renewable Resources, Latokartanonkaari 9, FI-00790 Helsinki, Finland

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ABSTRACT

Crop production in northern regions is projected to benefit from longer growing seasons brought on by future climate change. However, production also faces multiple challenges due to more frequent and intense extreme weather phenomena, and uncertain future prices of agricultural inputs and outputs. Extensive studies have been conducted to investigate the impacts of climate change on cereals yield change, but integrated assessments that also consider the management and economy of cereal farms have been rare so far. In this study, the effects of climate change-driven crop productivity change on farm level land use dynamics, input use, production management and farm income were considered from the point of view of dynamic decision making of a rational risk-averse farmer. We assessed whether a farmer can gain from improved crop yields when using adapted cultivars and managing the farm accordingly. We incorporated crop yield estimates from a process-based large area crop model (MCWLA) run with two climate scenarios into a dynamic economic model of farm management and crop rotation (DEMCROP) to investigate future input use, land use with crop rotation, economic gross margins and greenhouse gas emissions. A time span of 30 years was considered. The model accounts for the yield responses to fertilisation, crop protection, liming of field parcels, and yield losses due to monoculture. The approach resulted in a novel and necessary analysis of farm management, production and income implications of climate change adaptation under different climate and socio-economic scenarios. We analysed the effects of different climate and price scenarios at a typical cereal farm in the North Savo region, which is currently a marginal area for crop production in Finland due to its harsh climate. Crop modelling results suggest a 19–27% increase of spring cereal yields and 11–19% increase of winter wheat yields from the current level until 2042–2070. According to our economic farm level simulations, these yield increases would incentivise farmers towards more intense input use resulting in additional increase of yields by 3–8% at current prices. More land is allocated to barley and wheat, less to set-aside and oat. The economic gross margin would increase significantly from the current low levels. Greenhouse gas emissions from farms were estimated to increase with increasing production, but emissions per quantity produced (measured as feed energy units) would decrease. There is potential for sustainable intensification (SI) of crop production in the region.

1. Introduction

Climate change patterns and impacts have been witnessed and predicted to vary geographically across regions (IPCC, 2014). For northern Europe, a prolonged growing season (Ruosteenoja et al., 2016) and increased crop yields under projected climate change have been estimated (Bindi and Olesen, 2011; Höglind et al., 2013; Rötter et al., 2012) although the range in climate projections also allows for negative yield effects (Rötter et al., 2012). Recent literature suggests that in northern regions, such as in Finland, where agriculture is limited by short growing seasons, crop cultivars that are better suited to longer growing seasons are likely to provide increase in yield potential (Rötter et al., 2013; Tao et al., 2015; Palosuo et al., 2015). Especially, yields of cereal crops such as wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) may increase by 20–30% in some individual regions, such as North Savo region in central Finland, where e.g. cereals crop yields are currently below the national average in Finland (Tao et al., 2015). In fact the region is currently a marginal area for cereals production in Finland due to unfavourable climatic conditions. Yields of grass species like Timothy (*Phleum pratense*) may also increase remarkably in North

Savo region, even 10–15% (Höglind et al., 2013). These yield changes, if they come about, may have significant effects on production structure and land use in the region. Expansion of production in the currently marginal production areas may have significant societal and environmental consequences.

Development of agricultural production, however, is highly dependent on global markets, prices of agricultural inputs and outputs, as well as on agricultural policy that affect farmers actions via aids and regulations (Lehtonen, 2015; Mittenzwei et al., 2017). Farmers' use of fertilisers, pesticides, liming for soil improvement and drainage largely affect crop yield levels produced. However, sufficiently high market prices of agricultural commodities are required to cover the costs of such farm management practices. Input prices as well as crop prices in Europe are dependent on the realisation of global food demand and price developments. Any attempts to improve crop yields may be jeopardised by increasing prices of agricultural inputs or decreasing crop prices. In fact, price volatility as a remarkable source of uncertainty may significantly inhibit agricultural investments and the use of agricultural inputs (FAO et al., 2011). Hence, it is important to take account of the uncertainty of future mean price levels in our analysis of yield change driven impacts on future agricultural crop management and production.

Impacts of climate change on agricultural production in Europe have been studied in various countries by using bio-physical research results of crop yield changes in different climate scenarios as inputs for economic models of agriculture (Blanco et al., 2017; Dono et al., 2016; Mittenzwei et al., 2017; Özkan et al., 2017; Schönhart et al., 2016; Zessner et al., 2017; Zimmermann et al., 2017). Although these studies consider crop yield changes in a wider market, biophysical or policy context, they provide little explicit results or reasoning on farm level adjustments, e.g. use of different inputs, yield effects, production and overall management, due to changed crop yields. There are few, if any, studies that focus on farm level management changes, including change in the use of several inputs related to climate change driven crop yield changes. This however is important in northern Europe where crop yields and the use of yield determining inputs, such as fertilisation, fungicide use and liming, have been low and even decreasing due to low expectations related to crop prices, yields and policy incentives (Lehtonen et al., 2016a; Myyrä et al., 2005; Peltonen-Sainio et al., 2015). However if low yield potential and/or price expectations are changed that may trigger increased use of some yield determining inputs, and a further change in crop yields and farm income, depending to realised prices and yields. Dono et al. (2016) comprehensively studied farm level effects of climate change for some farm types in Italy focusing on water availability, temperature and related stochastic aspects of climate change. Studies of e.g. Mittenzwei et al. (2017), Özkan et al. (2017), Schönhart et al. (2016) and Zessner et al. (2017), can be considered as positive examples as well since they report some aspects of changed farm management, either land use patterns or the use of agricultural inputs, in addition to crop yield changes.

However there is a tendency of direct incorporation of crop yield changes, predicted by bio-physical models, into economic models, with little consideration of changed use of inputs and resulting responses. Such papers (e.g. Blanco et al., 2017; Nelson et al., 2014) may have other merits, however, if focusing on e.g. market feedbacks, global trade flows and price effects of climate change in large scales. Nevertheless, analysing changes in the use of multiple inputs simultaneously is important because they may have important responses on crop yields and farm economy. Such farm level analysis, with related dynamic aspects of responses and farm level decision making, are important and could be accounted for when analysing impacts of climate change in larger scales and dimension. For example environmental effects of agriculture are likely to be dependent on the use of inputs, land use changes and crop yields (Huttunen et al., 2015; Schönhart et al., 2016). Even though many extensive studies have been conducted to investigate the impacts of climate change on cereals yield change, as mentioned

above, the integrated assessment of the impacts of climate change driven crop yield changes on management of cereals farms and their economy has been rare so far.

Agricultural production and its sustainable development in northern Europe - with potential benefits due to climate changes as well, not only negative consequences - is considered necessary due to sustainability concerns (Tilman et al., 2011) and expected large scale challenges on agricultural production in southern Europe (Dono et al., 2016) and elsewhere where climate change is expected to bring difficult negative consequences in a large scale (IPCC, 2014). Reaching higher crop yields with more effective use of inputs (better yield responses) seems to be a core issue of sustainable intensification (SI) (Tilman et al., 2011). Developing more adapted cultivars for future climate conditions is considered a major adaptation option in northern Europe (Peltonen-Sainio et al., 2009; Rötter et al., 2013).

In this study, we focus on dynamic farm management and implications of climate change on production, farm income, and include estimated effects on greenhouse gas emissions as well, in the context of northern Europe. Our objective is to find answers to the following research questions: What are the effects of crop productivity change on farm level land use, input use, production and farm income? What are the effects of improved crop yields to farm's profitability? How do the effects vary with different future price levels? What are the differences between spring and winter cereals in future climate conditions? Do higher crop yields lead to reduced GHG emissions per farm or per unit produced? To this end, we focus our analysis on adaptation to climate change by using new, more adapted crop cultivars and study the implications of their usage to production and farm management of cereals farms in the North Savo region. The yields of cereals crops are currently below the national average in the North Savo region. However the predicted increase in the cereals yields are relatively high, assuming more productive cereals cultivars (Tao et al., 2015). Our aim is to analyse the extent to which the productivity and profitability of the cereals farms in the region may improve due to more adapted cultivars to future climate. We bring the crop yield benefits of adapted cultivars, predicted by bio-physical crop modelling, into a dynamic decision making of a rational risk-averse farmer. We use an economic modelling approach that considers the yield potential of adapted cultivars, but also accounts for the yield responses of changed fertilisation, crop protection, liming of field parcels, and crop rotation, with yield losses due to monoculture, over a 30 year time period. Thus we analyse management, crop yield and income implications of more adapted cultivar under dynamic, economically rational decision making.

2. Materials and methods

2.1. Pilot region: North Savo, Finland

North Savo is a province in central part of Finland (Fig. 1) with 4.6% of total population in Finland and 6.4% of agricultural land area of Finland. Average size of cereals farms in this region is approximately 50 ha. 32% of farm family income at cereals farms in the region comes from agriculture (Lehtonen et al., 2016a).

Dairy farms (10% out of whole Finland, average size appr. 35 cows and 50 ha) along with other cattle husbandry and cereal farms are the major agricultural production lines in this region (Lehtonen et al., 2016a). Consequently, a large share of farmland is occupied by specialised livestock farms and cereal farms. Yields of cereals are 20–39% lower than in the southern Finland. According to FADN data (Luke, 2017a), the average gross margin per hectare on all cereals farms in Finland was 234 €/ha 2010–2012, whereas the average gross margin per hectare at North Savo cereals farms was 198 €/ha 2010–2012, i.e. 17% less than the whole country average (data does not allow to compare the gross margins for the whole 2000–2015 period). At present, North Savo can be considered a marginal area for cereals production, producing mainly feed cereals for local dairy and beef
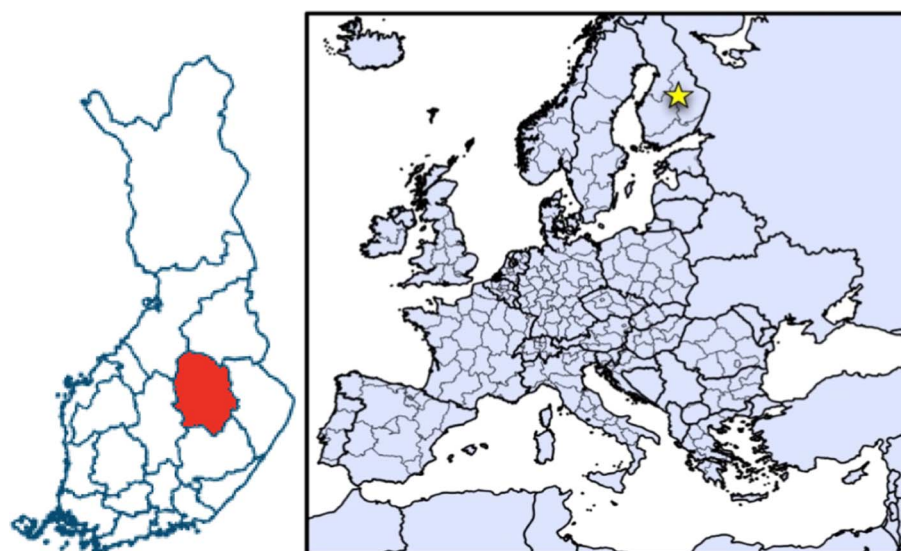
Fig. 1. Location of the North Savo region in Finland.
Source: MACSUR Regional case studies http://macsur.eu/index.php/regional-case-studies/.

production, but the region may have unexploited production potential in the future.

The average temperature in North Savo is expected to increase from current $-8\,°C$ by $+3–9\,°C$ in winter and from $16\,°C$ by $+1–5\,°C$ in summer until 2100, depending on the climate scenario (Ruosteenoja et al., 2011). Annual precipitation is expected to increase from the level of approximately 700 mm/year by $+12–22\%$ annually. Precipitation is expected to increase more in winter time ($+10–40\%$) and less in summer time ($+0–20\%$). The main direct impacts of climate change on agriculture in the North Savo region are higher temperature sum during the growing period, prolongation of the growing period and higher probability of temperature stress during yield determination period (Rötter et al., 2012). Particularly on sandy soils more severe effects of droughts are possible if no adaptation such as supplementary irrigation takes place (Rötter et al., 2013).

2.2. Methodological framework

Fig. 2 presents the structure of the simulation framework used in this study: the DEMCROP model (Liu et al., 2016) and its interaction with biophysical model MCWLA (Tao and Zhang, 2013) as well as price and policy assumptions. In details, first, a process-based large area biophysical model MCWLA is run with selected climate scenarios to simulate the future yield development in North Savo region. The projected yields are used as a proxy for yield in the region (See details in

Section 2.3). Finally, using these yield projections together with farm management input (fungicide, liming and labour etc.) at farm level and social economic drivers (prices and policy regimes), DEMCROP can dynamically and simulate farmer's optimal long-term economic decisions. MCWLA estimates crop yields under baseline climate (1971–2000) and future simulations (2042–2070) were assuming currently typical, relatively low-level fertilisation and crop protection in the region. Those estimates were very close to the actual observed crop yields between 1995 and 2015 DEMCROP uses MCWLA results on yield changes under different climate scenarios with respect to baseline. However DEMCROP may change the use of fertilisation, fungicide and liming, and may affect crop yields as well if it is economically profitable. We evaluate the model outcomes at different expected future price levels to investigate the sensitivity of the effects of yield level changes from the exogenous crop prices. Consequently, crop yields and input use at the farm, optimal products portfolio and land allocation as well as crop rotation patterns and farm gross margin are simulated as results under different climate change and prices scenarios.

2.3. Impacts of climate change on crop yields estimated by the biophysical MCWLA model

Tao et al. (2015) assessed climate impacts on spring and winter wheat yields and water use in different regions in Finland using an ensemble probabilistic approach. Crop yields were simulated using a
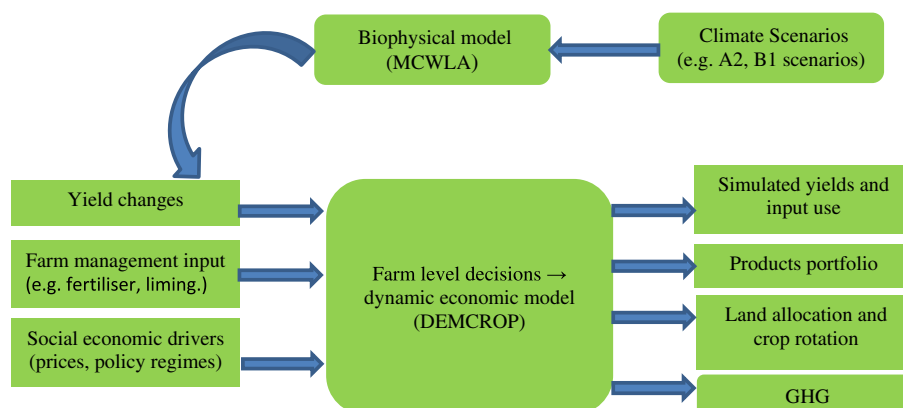

Fig. 2. The framework of this study using bio-physical simulation results on crop yields and other data in DEMCROP model.

process-based large area crop model (MCWLA), taking into account the typical soil properties such as soil-texture dependent percolation and water holding capacity in the region. The model is designed to investigate the impacts of weather and climate variability (and change) on crop growth, development, and productivity for a large area. It is explicitly parameterised for the effects of extreme temperature and drought stress on wheat yields, and accounted for a wide range of wheat cultivars with contrasting phenological characteristics and thermal requirements by using multiple sets of model parameters. MCWLA has been extensively tested to simulate the impacts of climate variability and elevated carbon dioxide (CO_2) concentration on wheat growth and yields in China (Tao and Zhang, 2013) and in other major production areas (Asseng et al., 2013), suggesting that it is also useful for impact assessment under future climate (Tao et al., 2009).

Concerning North Savo region, Tao et al. (2015) used 20 sets of crop model genetic parameters to represent genetic variations of wheat cultivars. This makes future crop yield change projections more robust than relying on a single or few sets of genetic parameters. These 20 virtual cultivars have ranges in some cultivar traits, such as high temperature tolerance, maximum leaf area index, photosynthesis capacity, etc., that are assumed to cover the genetic variations of wheat cultivars at present and in the near future. Therefore, the resulting yield projections consider the changes in cultivars in a direction that makes them more suitable for future climate conditions. However, sensitivities of future yield changes were not quantified in much detail by Tao et al. (2015). Hence we used the results of Tao et al. (2015) to represent mean crop yield changes, not crop yield variance changes, in future climate.

Using the optimal 20 (10) sets of parameters for spring wheat (winter wheat), MCWLA was driven by the baseline climate conditions (1971–2000) and future climate scenarios for the 2020s (2011–2041), 2050s (2042–2070), and 2080s (2071–2100), respectively, resulting in a super ensemble-based projection (more details in Tao et al., 2015). We used the 2050s scenario in our DEMCROP model simulations. The MCWLA simulations were conducted for B1 and A2 climate scenarios. The IPCC based B1 emissions scenario can be considered low/medium global warming scenario and corresponds closely to the more recently specified RCP 4.5 scenario, while A2 can be considered somewhat closer to RCP 8.5 (strong radiative forcing and high temperature increase) (Nakicenovic et al., 2000; Rogelj et al., 2012; van Vuuren et al., 2014). Temperature stress and adverse weather conditions are more frequent in A2 than in B1. MCWLA accounts for this variability and CO_2 effects in these climate scenarios as well, not only the sum of prolongation of the growing season and increasing temperature (Tao et al., 2015). Results of four General Circulation Models (GCMs; BCCR, GISS, IPSL and CSIRO) from CMIP 3 archive (Meehl et al., 2007) for these emission scenarios were downscaled as described in Rötter et al. (2013). It is a general practice in climate impact studies that output of several GCM's are utilized to cover uncertainty related to climate modelling. Here we chose the following scenario-GCM combinations: B1 GISS (the most modest warming, slightly increased precipitation), B1 CSIRO (moderate warming, nearly no change in precipitation compared to current levels), A2 BCCR (high warming with increased precipitation) and A2 IPSL (the highest warming with decreased precipitation). For more details about these climate scenario results for Finland are reported in Rötter et al., 2013.

According to the results of Tao et al. (2015), yields of spring barley and spring wheat develop very similarly. However, yields of winter wheat in all emission scenario-climate model combinations developed in a different manner, partly due to climate change impacts on temperatures and precipitation outside the growing period (Fig. 3a and b). Compared with spring wheat, the development, photosynthesis, and consequently yield was much less enhanced for winter wheat, and so yield increase of winter wheat was significantly smaller than the yield increase of spring barley and spring wheat in the bio-physical model simulations. Consequently, we assume in this study that yields of all

spring crops (spring wheat, barley, oat and spring turnip rape) will develop in a very similar way. The results from the MCWLA model suggest a 20–30% increase in mean yields from current climate to mid-century climate in A2 and B1, but relatively small changes in inter-annual crop yield variability (Fig. 3c and Table 1). In the case of winter wheat the standard deviation of the yields is smaller in the future scenarios than the standard deviation of the average yields in the region in the baseline. However these two standard deviations are not directly comparable. Average regional yields of winter wheat are not available for every year in the statistical (baseline) data. Winter wheat often suffers from wintertime crop damage, and the areas of winter wheat are often re-sown for spring cereals in spring. We consider the statistical basis for winter wheat yields rather weak. Since gross margin variability of crops is dependent on both yield variability and input and output price variability as well, not forecasted to the distant future, we assume gross margin variability unchanged from the 1995–2015 period in the economic DEMCROP model. This has some implications on the model results as will be shown and discussed later.

Farm economic DEMCROP model, presented in the next section is used to simulate economically rational farm management in B1 GISS and A2 APSL scenarios representing the highest and lowest yield developments, respectively, in Table 1. We see that these scenarios, when run using the farm economic model DEMCROP, provide the most interesting results in terms of farm management and economy.

2.4. DEMCROP model

DEMCROP (Liu et al., 2016) allows us to solve dynamic inter-temporal decisions in a long time span (30 years) without excluding short-term decisions affecting only one or a few years. We use a generic version of the model here, validated and used already by Lehtonen et al. (2016a), for simulating the average land use, crop rotation and crop and field parcel specific management of cereal farms in the North Savo region. We first validate the model by updating the data.

How the model works is, briefly, as follows (see Liu et al., 2016 or Lehtonen et al., 2016a for more details and example applications). We assume a rational risk-averse farmer who maximises his/her expected income at present value discounted from future streams of expected gross margin, while minimising the variance of expected gross margins. By choosing the sequence of crops planted every year during a period of 30 years, the economic modelling approach taken here is directly compatible with the time spans of 20–30 years used in crop modelling studies in climate change context (e.g. Tao et al., 2015), with risk aversion considered, the corresponding DEMCROP can be formulated and solved by nonlinear programming in the following:

$$Max \sum_{t=1}^{30} \sum_{p}^{10} \sum_{i=1}^{M} \frac{1}{(1+r)^t} (Y(A(p,t,i),p,t,i)A(p,t,i)P(i) + S(i)$$
$$- C(p,t,i)) - \theta \sum_{t-1}^{H} \sum_{c} \sum_{c2} \frac{1}{(1+r)^t} A'XA \tag{1}$$

subject to

$$\sum_{\forall i} A(p,t,i) = 1$$

A(p,t,i) is area allocation for crop c on time (year) t, at field parcel p, Y(·) is crop yield level, dependent on prices p, past area allocations on field parcel p (due to yield losses due to monocultural cultivation; see appendix), P(·) is crop market price, S(·) is subsidy paid per hectare, and C(·) is cost per hectare.

The first row in (1) is gross margin in monetary terms, while the second row represents variability of the gross margin, multiplied by a risk aversion constant. The covariance matrix X is based on gross margin variability of all crops 2000–2015, and is kept unchanged in all simulations. Since gross margin depends on variability of output and input prices as well as covariance of crop yields we do not consider it
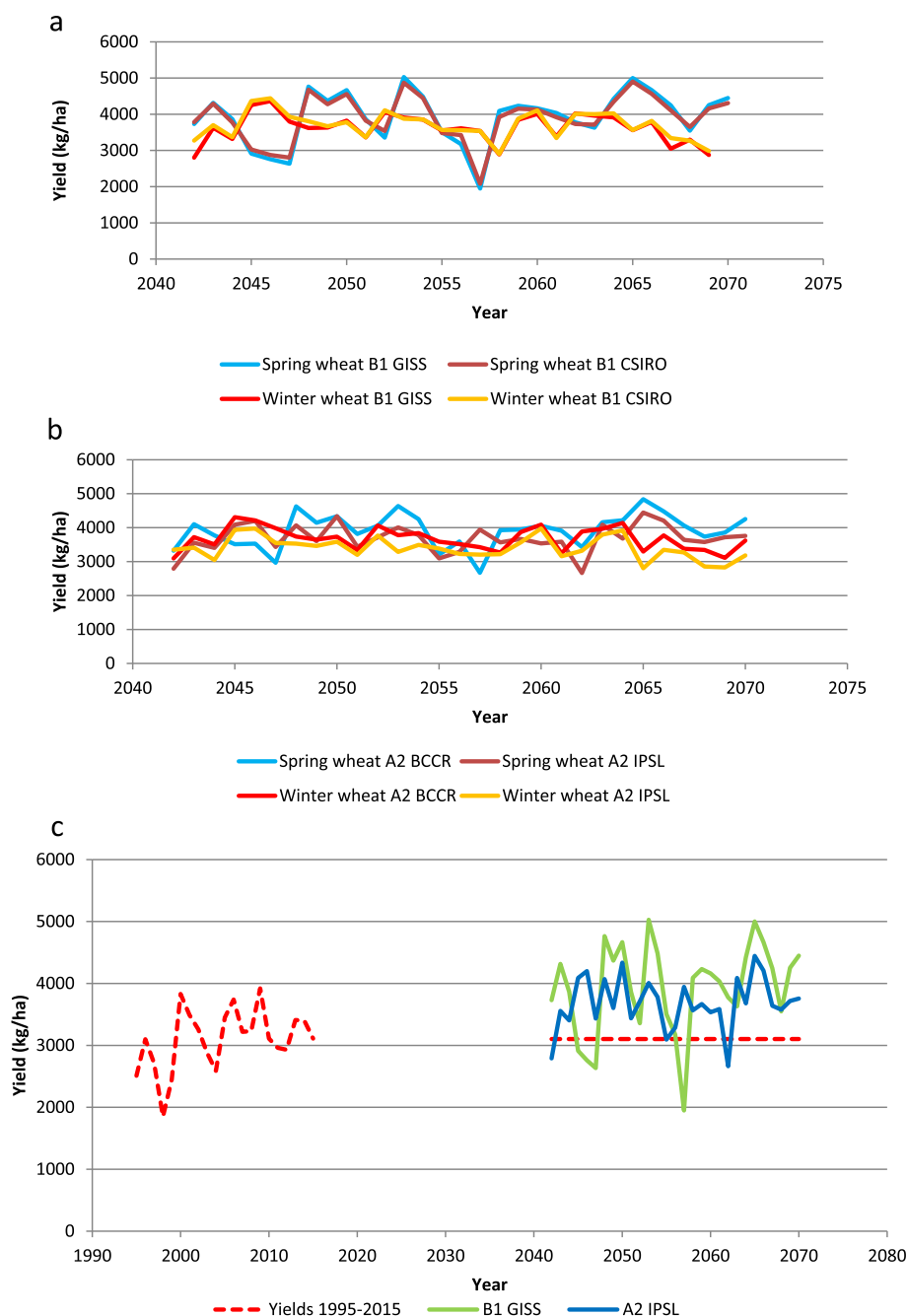
Fig. 3. a. Simulated yield result from MCWLA in B1 climate scenarios 2042–2070. b. Simulated yield result from MCWLA in A2 climate scenarios 2042–2070. c. Historical yield of spring wheat in North Savo region 1995–2015 (Luke, 2017a, 2017b, 2017c; Tike, 1996–1999) vs. simulated yield of spring wheat under climate scenarios B1 GISS and A2 IPSL 2042–2070.

feasible to estimate future changes in gross margin variability. The risk aversion coefficient is used as a calibration coefficient after validating all input and output prices and subsidy information.

We assume that a farm is split into 10 parcels, whose distances to the farm centre are continuously increasing at even steps of additional distance 0–7 km, providing an average distance of 2.9 km in the region (Hiironen and Ettanen, 2013). Nine field parcels are assumed to be of the mineral soil type, which is the dominant soil type in the region. One parcel is of organic soil type, with significantly higher greenhouse gas emissions than other parcels, located at distance of two kilometres from the farm centre. This setting is due to the fact that about 10% of agricultural land area is of organic soil type in the North Savo area (Viljavuuspalvelu, 2017). Additionally, we include five crops that are the most common in the North Savo region (see Table 2) plus two types

of set-aside lands (M = 7). Nature management field (NMF) implies higher costs than set-aside since NMF is given more specific conditions. To compensate this, NMF is paid higher subsidy. By support conditions, the area of NMF is restricted to 15% of overall land area and sum of set-aside areas cannot exceed 50%.

Cultivation in distant parcels implies high logistic costs, calculated in the model based on management actions implying tractor driving times, fuel consumption and labour use provided by Seppälä et al. (2014). Crop specific management activities include fertilisation, fungicide use (for barley and wheat) and crop rotation, all with yield response. Liming of field parcels implies yield effects for all crops. The model therefore solves for optimal crop sequencing, land use and liming at different field parcels, as well as crop specific fertilisation and crop protection activities for a 30 year time period, accounting for both

Table 1
Observed (1995–2015) (Luke, 2017a, 2017b, 2017c; Tike, 1996–1999) and estimated future scenario (2042–2070) means and standard deviations of yields for spring wheat and winter wheat at North Savo region.

	Observed 1995–2015	MCWLA simulated yields 2042–2070			
	Baseline	B1 GISS	BI CSIRO	A2 BCCR	A2 IPSL
Spring wheat average (kg/ha)	3102	3927	3909	3910	3685
Spring wheat s.d. (kg/ha)	499	734	645	497	416
Winter wheat average (kg/ha)	3056	3623	3686	3671	3402
Winter wheat s.d. (kg/ha)	723	399	374	335	328

Table 2
Average input data consisting of crop yields, variable costs and subsidies used in the model.

Crop	Average yield kg/ha $Y_{MEAN}(p,c^i)$	Average output prices €/kg $P(i)$	Variable cost €/ha[a] $C_{variable}(c^i)$	Subsidy €/ha $S(c^i)$
Spring wheat	3086	0.138	544	575
Winter wheat	3051	0.138	590	584
Barley	3096	0.131	497	525
Oat	2785	0.121	479	525
Spring turnip rape	1305	0.320	563	593
Set-aside	–	–	147	375
NMF[b]	–	–	167	428

[a] Costs consist of seeds, herbicides, machinery, share of current assets and interest and share of fungicides, fertiliser and liming that are needed to reach average yields.
[b] Nature management field.

expected profits, and risk behaviour, i.e. avoiding farm level gross margin variability (Liu et al., 2016). For a formal and detailed description of the full model, please refer to the Appendix.

The model application in this study is made for a case of an average cereals farm (50 ha) in North Savo region, with average land allocation of cereals farms found the regional statistics. We assume this farm type to remain unchanged in this study. This means that farm capital and labour productivity does not change, but use of variable inputs and crop yields might change. We do not include capital investments in this model application since we consider climate change adaptation effects only and do not consider structural or technological changes in this study. Hence our results show what more adapted crop cultivars outlined and studied by Tao et al. (2015) contribute at current cereals farms in the North Savo region. Later studies, with also socio-economic scenarios with technical and market changes, can show possible overall changes at the farm level.

2.5. Input data

2.5.1. Historical yield, cost, subsidy and price data

Historical data comprised 21 years (1995–2015) for crop yields, prices of inputs and outputs (Statistics Finland, 2017; Luke, 2017c), variable costs and subsidy data, used in the baseline scenario (no climate change) in the DEMCROP model, were extracted from various sources regarding North Savo region in Finland (Table 2). The average yield is the mean value of annual yield over 20 years obtained from official agricultural statistics of Finland (Luke, 2017b; Tike, 1996–1999). The averages of variable costs and subsidies of the crops are derived from a recent version of a dynamic regional sector model of

Finnish agriculture (DREMFIA) (Lehtonen, 2001, 2015), which provides validated approximations of the average use of inputs per crop in each region. Variable inputs and costs are presented in Table 2.

2.5.2. Parameters fungicide treatment and liming

Fungicide treatment efficiency is based on field trial estimates in various locations around Finland in 1999–2010 in the case of barley (Purola, 2013) and 1999–2013 in the case of wheat using same estimation methods. On average, efficient fungicide treatment can increase yields by 11.7% (wheat) and 12.7% (barley). Based on Mäenpää's (2010) survey, slightly over 60% of farms in the 20–50 ha size range use fungicides. The survey was conducted by internet survey, mainly attracting farmers who are eager to develop their farming practices. In this light, the results might overestimate fungicide use. Still, it is reasonable to assume that fungicide use in the North Savo cereals farms is significantly less than the average use in southern Finland, since cereals yields are 20% lower in the North Savo region. Costs caused by the fungicide, machinery or labour treatments are incorporated in the variable costs. There are no dynamic consequences: the treatment given in previous years does not affect the current year, nor is there increasing resistance against fungicide treatments.

The pH values of Finnish agricultural soils lie commonly between 4.5 and 6.5, whereas the most beneficial pH range for most plants is 6.5–7.5. Liming has long been recognised as an effective practice in Finland. Inorganic nitrogen fertilisation has a tendency to decrease soil pH values. Counterbalancing this, the DEMCROP model includes a liming activity that increases soil pH (Liu et al., 2016). Increasing soil pH by one unit increases crop yields by 10–15%, based on Myyrä et al. (2005). The costs of liming activity have been derived from available sources on lime spreading contract operations.

2.5.3. Yield penalty matrix for monocultural cultivation

Monocultural cultivation, i.e. cultivation of one crop on the same field parcel over several growing periods with no break, leads to crop yield reduction of the cultivated crop. The DEMCROP model keeps track of the cultivation history of each field parcel, and includes a yield penalty matrix that defines a yield loss of 1% for cereals if the same cereal as the previous year is cultivated in the same field parcel the following year (see Liu et al., 2016 for details). If one spring cereal follows another cereal crop, then a slightly lower yield loss of 0.5% is assumed. If a spring turnip rape crop is cultivated following spring turnip rape in the same field parcel the previous year, a 25% yield loss is assumed. These estimates are based on expert assessment and not on numerical data. This is a weakness of the model currently and can be improved if sufficient data is made available. However our conservative expert estimates are kept constant in all scenarios of this study and do not affect the main pattern of the results. The model keeps track of the five-year cultivation history of each field parcel. This is based on the empirical observation that spring turnip rape diseases may still be prevalent in the soil three to four years after spring turnip rape cultivation, but are largely absent five years from the last spring turnip rape cultivation (Peltonen-Sainio et al., 2007). This five year memory of cultivation history also implies that yield losses due to monoculture are cumulative over the five previous years, but do not accumulate any more from a longer time period than five years in the past. For example, yield losses of spring cereals caused by monoculture may accumulate close to 5% if the same cereal crop is allocated in the same field parcel for five years in a row, but the yield loss does not accumulate any longer if there are six or more years of monoculture.

However, if cultivating cereals, oilseeds, grass or set-aside in a sequence of any order in the same field parcel eliminates yield losses of monoculture. The model can move from monoculture to crop rotation. Nevertheless, logistic costs to the distant field parcels may imply, as has been observed in the reality, that distant field parcels are set-aside in case of low crop prices, whereas the nearest field parcels to the farm

Table 3

Scenario setting details for current (baseline) and future scenarios defined with emission scenario (B1 or A2), climate model (GISS, IPSL) for the time period 2042–2070 and with different output price levels.

		Price scenario		
		− 20% baseline price (LP)	Baseline price (BP)	+ 20% baseline price (HP)
Emission scenario – Climate model - combination	Baseline B1 GISS A2 IPSL	Baseline LP B1 GISS LP A2 IPSL LP	Baseline BP B1 GISS BP A2 IPSL BP	Baseline HP B1 GISS HP A2 IPSL HP

centre may still be allocated to the same or same kind of crops year after year. The model accounts for the full crop rotations per field parcel.

2.6. Scenario settings

Average crop prices in Finland for the year 1995–2015 are taken as baseline prices (BP). For the sake of sensitivity analysis, we assume 20% lower prices than baseline prices in a low price scenario (LP) and 20% higher prices than baseline prices in the high price scenario (HP). Combining the yield projections of the biophysical crop model with climate scenarios together with the price settings, we run DEMCROP to generate eight future scenarios listed in Table 3.

It is assumed in all scenarios that a 5% set-aside area is obligatory to meet ecological targets, e.g. water protection targets, of the North Savo region, as well as to maintain biodiversity. Following the current CAP rules for greening, we also assume that one crop should not be cultivated on > 75% of available farmland area of a farm annually in all scenarios.

2.7. Risk aversion calibration

Risk attitude/degree of risk aversion of a farmer is often significant in explaining farm management and land allocation decisions. However, the quantitative dimension of this risk response is more difficult to assess because results are typically not reported in a standardised manner (Moschini and Hennessy, 2001). Based on the mean-variance utility function, DEMCROP implicitly assumes constant absolute risk aversion (CARA). The assumption of CARA is valid on cereal farms in North Savo, where part-time farms are common and a large portion of household income comes from off-farm sources (Lehtonen et al., 2016a). We derive the risk aversion coefficient from the farm plan close to the farmers' existing practice following the approach of Liu et al. (2016). In detail, using historical data for selected crops and previously calibrated parameters of liming and fungicide treatment (Liu et al., 2016) under baseline price settings, we attempt to simulate the land use shares in the North Savo region with randomly selected risk aversion coefficients. Then, we compare the simulated results with the average of land use shares in the North Savo region obtained from Statistics Finland from 2000 to 2015 (See Fig. 4). Finally, the statistically best performing risk aversion parameter is chosen for the later scenario analysis. Fig. 4 displays the root-mean squared deviation (RMSD) values resulting from different risk aversion parameters. Clearly, θ = 0.0113 provides the best fit statistically and therefore is chosen for the scenario analysis. With this risk aversion co-efficient, the observed development in land use and yields were closely reproduced by the model (Fig. 4) and we found it reasonable to apply the model for evaluating land use and yield responses to changed crop yield potential and price conditions.

2.8. Calculating greenhouse gas emissions

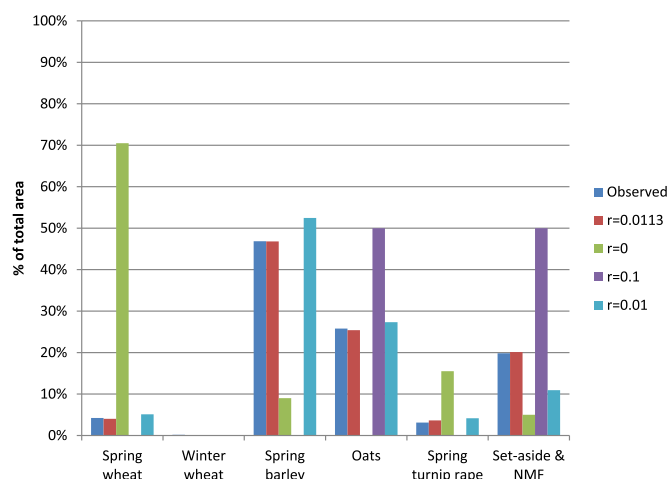Greenhouse gas (GHG) emissions are calculated in the DEMCROP

Fig. 4. Simulated average area coverage of selected crops with a range of risk aversion coefficients vs. average of observed area coverage 2000–2015.

model based on the IPCC method applied in Finland and its parameters (see Lehtonen, 2012 and Statistics Finland, 2017 for details). Lehtonen (2012) applied the IPCC calculation scheme in a nationwide agricultural sector model. The GHG emission calculation applied by Lehtonen (2012), not including e.g. horses and reindeers, calculated approximately 95% of the GHG emissions reported in the official national inventory. We apply the same calculation scheme, excluding nitrogen processes in animal husbandry (not part of the DEMCROP model). Parameters and the calculation are kept fixed in DEMCROP and are not changed between the baseline and the different climate scenarios. The resulting GHG emissions should be considered indicative only since they do not take into account changes in, e.g. biophysical soil processes due to climate change. The purpose of the GHG emission calculation in this paper is to show an estimate on the effects of changed farm management (production, land use and input use) on GHG emissions, given the changed crop yield potential in different climate scenarios. The reported GHG emissions here could be considered valid if no major change is assumed or expected in the GHG emission calculation scheme or in related parameters.

3. Results

3.1. Production and gross margin in 30 years' time span under the current climate

3.1.1. Baseline price scenario

Simulated land allocation matches quite well with historical land allocation in the calibration runs, and average baseline yields are close to the actual average yields in the area 1995–2015 (see Table 4). Average pH (6.01) is within 5.8–6.1, which is a typical soil pH range on different soil types in Finland (Myyrä et al., 2005). Fungicide treatment is given to about 20% on barley and spring wheat area. Set-aside is located mostly at distant parcels where logistic costs are high. Field parcels of organic soil type, 10% of the farmland area of the region, are often on set-aside due to lower yield expectations. This is largely due to low soil pH, which affects yields of cereals in particular. Gross margin per farm (180 €/ha) is relatively low in the baseline. According to FADN data, the average gross margin per hectare at North Savo cereals farms was 198 €/ha for the period 2010–2012 (Luke, 2017a). However gross margins and profitability of cereals production have been relatively low in Finland since 2013 but the data is not sufficient to show the profitability of North Savo cereals farm 2013–2015 when crop prices were low (Luke, 2017a). We consider our modelled gross margin to be a relatively realistic result for the baseline, at average prices. Total production, calculated as feed energy content of the crop, for bovine

Table 4

Average observed yields of crops used in the model in the North Savo region 1995–2015 (Luke, 2017b; Tike, 1996–1999) and simulated yields, fungicide treatment, pH values of parcels, average gross margins per ha and GHG emissions from economic model simulations for the baseline with different price options: LP stands for low prices, BP baseline prices and HP high prices.

	Average yields 1995–2015	Simulated baseline yields from economic model		
		LP	BP	HP
Spring wheat	3102	2899 (−6.5%)	3040 (−2.0%)	3325 (+7.2%)
Winter wheat	3056			
Barley	2922	2731 (−6.5%)	2847 (−2.6%)	3149 (+7.8%)
Oat	2738	2576 (−5.9%)	2647 (−3.3%)	2802 (+2.3%)
Spring turnip rape	1291	1211 (−6.2%)	1272 (−1.5%)	1355 (+5.0%)
Percentage of fungicide treated area of total area for barley		0%	21%	100%
Percentage of fungicide treated area of total area of spring wheat		0%	19%	100%
Average pH/farm		5.71	6.01	6.52
Average gross margin €/ha		129 (−29%)	180	249 (+38%)
Total production, TJ/farm		227 (−38%)	365	479 (+31%)
Average GHG emissions tons CO$_2$ eq/ha		2.39 (−22%)	3.06	3.48 (+13%)
GHG emissions tons CO$_2$ eq. /GJ		0.158 (+26%)	0.126	0.109 (−13%)

animals, is 365 TJ, at the farm with 50 ha. GHG emissions are 3.06 tons CO$_2$ eq. per ha and 0.126 per (feed energy) unit produced. Most of the emissions come from the field parcel of organic soil type.

3.1.2. Low-price scenario

Extensive production takes place in the low-price scenario. Price reduction by 20% from the baseline prices decreases total production by 38%. Smaller amounts of inputs are used due to low crop prices. This can be seen in lower pH values in the soil, ceasing use of fungicides use and in lower simulated yields (Table 4). Price change also changes land allocation (Fig.5). In this scenario, half of the land area is allocated on set-aside that is the maximum area possible under the support conditions. The model representing a utility maximising farmer adjusts to lower prices by increasing the set-aside area, to reach low variable costs and still to keep agricultural support payments. Despite this adjustment, the proportional drop in average gross margin (29%) is higher than drop in crop prices. Some changes also occur in land allocation of crops. The area reserved for growing oat decreases significantly. In the base scenario with baseline prices, oat was cultivated frequently because of its role as a low risk crop. Area under oat decreases when prices decrease, and set-aside, with low risks becomes more tempting for a typical risk-averse farmer. The area for growing barley decreases also significantly, though not as dramatically as for oat. Spring turnip rape as a good break crop for cereals maintains its area when prices decrease. Overall GHG emissions decrease by 22%, which is much less than the decrease in total production. This is because farmlands, especially organic soils, produce GHG emissions even without any nitrogen fertilisation. This can be seen in emissions per energy content produced that are 27% higher than in the baseline scenario.

3.1.3. High-price scenario

When we move from the baseline price scenario to the high price scenario, production intensifies (Table 4). Liming is applied more often and fungicide treatment is given for spring wheat and barley every time they are cultivated. This leads to higher yields compared to the baseline

scenario price scenario. As output prices increase, more land is allocated to production (Fig. 5). Distant parcels that were allocated mostly to set-aside in the baseline price scenario are now allocated to crops more often. Only the minimum area required by the support conditions is allocated to the set-aside. Set-aside area if shifted mostly to barley. Farmland allocated for barley increases to 63% of land area. Barley takes also some land area from oat. Land allocation for spring wheat and spring turnip rape increases slightly. Total production increases by 31%. Although production is increasing significantly, greenhouse gas emissions increase only by 13%. Emissions per feed energy unit produced decrease by 13% compared to the baseline scenario. When prices increase by 20% from the baseline average price level, the average gross margin per farm increases by 38%. This is affected by higher crop yields and land use change, e.g. less set-aside and more land allocated on crops.

3.2. Production and gross margin in 30 years' time span under future climate scenarios in the 2050s

3.2.1. B1 GISS scenario

From the point of view of projected yields, the B1 GISS (low/medium) scenario is the most favourable for a typical cereals farmer of the future climate scenarios in terms of production volume and gross margin (see Table 5). This is why we show the results of that scenario. Management practices with current prices are more intensive than in the baseline scenario. Liming is applied often to keep the soil fertile. Fungicide treatment is given every time spring wheat and barley are cultivated. The set-aside area decreases to the assumed minimal level (5%) (Fig. 5) required by current ecological area conditions, or by current and future challenges of nutrient leaching abatement (Huttunen et al., 2015). The set-aside area decreases from baseline levels and land is increasing used for barley, spring wheat and spring turnip rape. Land area under oat decreases. Barley dominates production but the area used for growing spring wheat almost quintuples compared to the low wheat production areas in the baseline scenario. Area under spring wheat covers now almost 18% of the total area. Overall area under spring wheat and barley increase to 76% of total area that is significantly higher than in the baseline. This can be considered a shift towards spring cereals monoculture, since barley and spring wheat are more susceptible to plant diseases when cultivated in sequence (Shipton, 1977). The area under spring turnip rape - a good break crop in rotation - increases slightly. Total greenhouse gas emissions are higher than in the Baseline BP scenario (Table 6) caused by higher production and a smaller set-aside area. However, emissions per feed energy unit produced are approximately 35% smaller, due to higher productivity implied by better-adapted adapted cultivars and increased use of inputs such as liming and fungicide. Also changes in the crop allocation reduce the emissions per feed energy unit. The areas previously used for growing low-energy content oat are increasingly used to grow higher-energy content crops.

Under the B1 GISS scenario with substantially increased crop yields, it would be beneficial to increase the use of inputs from current levels even at prices 20% below the baseline prices (Table 5). A typical farm would also allocate land for crop production and allocate slightly more than the minimal area required (due to ecological conditions) for set-aside. Fungicide treatment and liming are intense compared to the baseline average price (BP) scenario. Total GHG emissions are even higher than in the Baseline BP scenario. But again, emissions per energy unit produced are significantly lower.

When output prices increase 20% from baseline prices in the B1 GISS scenario, the use of liming and fungicide increase but total production increases only 3% (Table 5). Farming is already intense with baseline prices in the B1 GISS scenario and there is relatively little room for further intensification, despite 20% higher prices, because the use of inputs is already at a relatively high level at average prices, and relatively little yield increase can be attained when increasing the use of
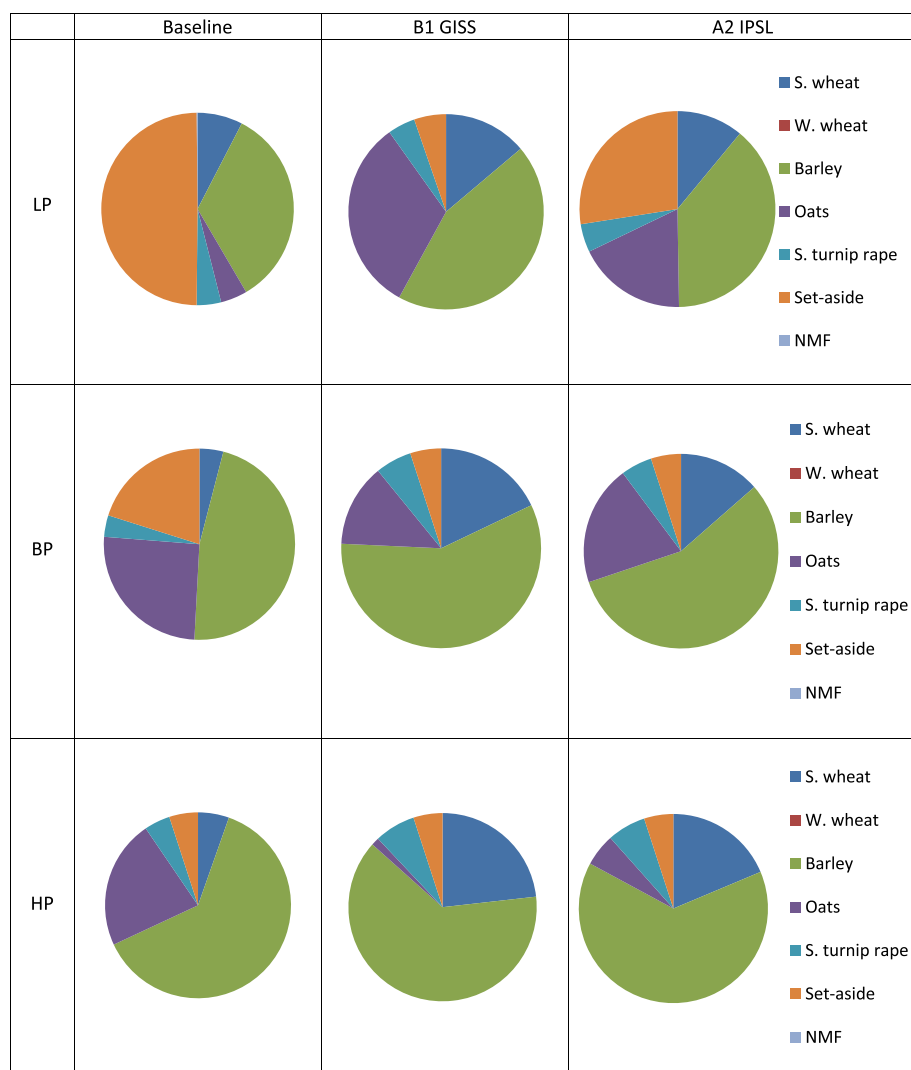
Fig. 5. Average land allocation under current climate, B1 GISS and A2 IPSL scenarios with different price scenarios: LP denotes low prices, BP baseline prices and HP for high prices.

inputs even further. However the gross margin per farm increases still relatively more (+25%) than the crop prices (20%). GHG emissions and total production increase almost the same percentage if prices increase by 20% in B1 GISS scenario. As output prices increase, the area used for growing spring wheat, which is higher priced than barley in all scenarios, increases relatively more than the area for barley, but barley maintains its position as a dominant crop in the area (Fig. 5). Barley and spring wheat take even more land area from lower priced oat when crop prices increase. Increase in gross margin, caused by increased yield potential and increase in output prices, makes spring wheat a more profitable crop. This being so, the area for spring wheat increases despite the fact that its gross margin variability is higher than that of barley. In the current climate, however, barley strengthens its position as a dominant crop when output prices increase.

3.2.2. A2 IPSL scenario

We chose A2 IPSL as another future scenario because its simulated future yields for 2050s scenario are the lowest of all MCWLA simulations. A2 IPSL is not as favourable to a typical farm as B1 GISS, in terms of crop yields and average gross margin, but it also offers opportunities for a typical farm to intensify production, compared to current climate (Table 5). With baseline prices, land allocation moves in the same direction as in B1 GISS scenario but not as dramatically (Fig. 5). Set-aside area reaches the minimum (5%) required by ecological area conditions.

The area for spring wheat increases remarkably but the increase is not as big as in B1 GISS scenario. Barley dominates production, but the area for growing oat does not decrease as much in B1 GISS scenario. Still there is a tendency towards barley and spring wheat monoculture. Overall GHG emissions are almost the same as in B1 GISS scenario, but emissions per feed energy unit of harvested crop are higher in the A2 IPSL scenario (Table 6).

Noticeable differences between future climate scenarios can be seen in low price scenarios. Although the production is intense even with low prices in the B1 GISS scenario, this is not the case in A2 IPSL where the use of inputs is almost as low as in the current climate with low prices. Crop prices are a strong driver of input use affecting yields despite significantly increased crop yield potential. However the increased yield potential increases land area used in production. 27% of land area is used as set-aside in the A2 IPSL low price scenario, which is significantly lower than in the current climate with low prices.

GHG emissions per feed energy unit produced are slightly higher than in B1 GISS scenario with current and high price scenarios. In the low price scenario emissions per total production (feed energy unit) produced are high compared to B1 GISS scenario, but they are still significantly lower than in the baseline scenario with low and current prices.

Effect of output price increase is similar to B1 GISS scenario. The area for spring wheat increases relatively more than the area for barley

Table 5
Simulated yields, fungicide treatment, pH values of parcels, average gross margin per ha and GHG emissions from economic model simulations for future climate scenarios B1 GISS and A2 IPSL [compared to the baseline].

Regional average yields kg/ha	B1 GISS				A2 IPSL			
	Simulated yield (MCWLA)	Simulated yield (economic model, DEMCROP)			Simulated yield (MCWLA)	Simulated yield (economic model, DEMCROP)		
		LP	BP	HP		LP	BP	HP
Spring wheat [3086][a]	3927	4088 (+2.1%)[b]	4220 (+7.5%)[b]	4233 (+7.8%)[b]	3685	3422 (−7.1%)[c]	3955 (+7.3%)[c]	3968 (+7.7%)[c]
Winter wheat [3051][a]	3623				3401	–	–	–
Barley [2948][a]	3699	3847 (+4.0%)[b]	3992 (7.9%)[b]	4006 (+8.3%)[b]	3471	3223 (−7.1%)[c]	3741 (+7.8%)[c]	3754 (+8.2%)[c]
Oat [2785][a]	3466	3491 (+0.7%)[b]	3571 (+3.0%)[b]	3621 (+4.5%)[b]	3252	3046 (−6.3%)[c]	3335 (+2.5%)[c]	3378 (+3.9%)[c]
Spring turnip rape [1305][a]	1634	1693 (+3.6%)[b]	1721 (+5.3%)[b]	1732 (+6.0%)[b]	1533	1459 (−4.8%)[c]	1610 (+5.0%)[c]	1623 (+5.8%)[c]
Percentage of fungicide treated area of total area for barley	61%	100%	100%		0%	100%	100%	
Percentage of fungicide treated area of total area for S. wheat	37%	100%	100%		0%	100%	100%	
Average pH/farm [6.02]	6.40	6.55	6.60		5.71	6.53	6.58	
Average gross margin €/ha [180]	218 (−24%)	286	356 (+25%)		172 (−33%)	259	325 (+25%)	
Total production, TJ/farm [365]	577 (−7.3%)	624	642 (+3.0%)		380 (−34%)	575	595 (+3.4%)	
Average GHG emissions tons CO_2 eq/ha [3.06]	3.24 (−3.7%)	3.37	3.51 (+4.0%)		2.84 (−16%)	3.37	3.50 (+3.8%)	
GHG emissions overall tons CO_2 eq. per GJ / [1.24]	0.084 (+3.9%)	0.081	0.082 (+1.0%)		0.112 (+28%)	0.088	0.088 (+0.3%)	

[a] Observed yields in the North Savo region.
[b] Yield increase compared to MCWLA simulations of B1 GISS scenario.
[c] Yield increase compared to MCWLA simulations of A2 IPSL scenario.

Table 6
Simulated barley yields, total crop production, gross margin per farm, GHG emissions for different climate scenarios with baseline prices and GHG emissions per feed energy unit produced for every scenario.

	Baseline BP	B1 GISS BP	A2 ISPL BP
Barley yield (kg/ha)	2847	3992 (+40%)	3741 (+31%)
Total crop production (feed energy content, TJ)	365	624 (+71%)	575 (+57%)
Average GHG emissions tons CO_2 eq/ha	3.06	3.37 (+10%)	3.37 (+10%)
Emissions per feed energy unit	0.126	0.081 (−35%)	0.088 (−30%)
Average gross margin €/ha	180	286 (+58%)	259 (+44%)

but the higher gross margin variability of wheat compared to barley keeps barley the dominant crop in the region.

4. Discussion

Crop modelling results suggests a 19–27% increase of spring cereals yields and an 11–19% increase of winter wheat yields from the current level until 2041–2070 with new cultivars in scenario A2 and B1 in the North Savo region. If these levels could be realised, it would also incentivise farmers for more intense input use, which could lead to an additional increase of yields by 3–8%, according to our dynamic economic farm level simulations. Farm income would increase significantly (44–58%) assuming current price levels. Even in the low price scenario, with favourable climate scenario (B1 GISS) farm income would increase 20% compared to the current climate with baseline prices.

Future climate is projected to be more favourable for spring cereals than for winter cereals in the North Savo region. Our results based on optimised farm management with risk aversion suggest this could lead to the disappearance of winter wheat cultivation from its already low levels.

Increasing yield potential could encourage risk-averse farmers to increase the production of spring wheat, the production of which production is low in the present climate due to its uncertainty. Both prices and yields of wheat have been more volatile compared to barley in the

region. If higher yield potential realise, both spring wheat and barley would increase its area significantly, but spring wheat area would increase relatively more. Increase in spring wheat and barley areas would happen in the expense of set-aside and oat. Oat is a favourable crop in the current climate due to lower costs per hectare and its more stable gross margin. However, if higher crop yields do come about, then oat is likely to be replaced by crops with higher price or yield potential. Spring turnip rape as a good break crop for cereals would become slightly more favourable in the future climate.

Increasing yields and more intense input increases production, and thereby also total greenhouse gas emissions from farms, by 10%. However, emissions per quantity produced, here measured as feed energy unit produced, would decrease by 30–35%. Emissions per feed energy unit would be lower than the current per unit emissions also in the low price scenarios. This shows that if cultivar breeding is successful, there might be possibilities for sustainable intensification, aiming for a simultaneous increase in agricultural production and reduced negative effects of agriculture on the environment through efficient farm and crop management practices (Tilman et al., 2011), in northern conditions in agriculture in the future.

However, we have not calculated the impacts of higher yielding cultivars and implied production changes on nutrient leaching, due to the lack of validated nutrient leaching functions at cereal farms in the region. Nutrient leaching has been a focal point of agri-environmental schemes implemented in Finland, and so this aspect should be analysed in more detail in the context of sustainable intensification. However, greenhouse gas mitigation is becoming increasingly important as a policy target.

According to Rötter et al. (2012) it is possible that cereal yields could decrease in the future with current cultivars, even though increasing yields are expected in the case of cultivars more suitable to future climate conditions. Our results, showing significant crop yield increase in both B1 and A2 scenarios, emphasise the importance of crop breeding for the climate in the future. More suitable cultivars for future climate conditions may have significant implications for economic viability and production volume of agriculture in the North Savo region, which must be considered as northern margin of agriculture currently due to low and uncertain cereals yields. Furthermore, increasing weather variability and heavier rains (Lehtonen et al., 2016b)

may endanger the harvest conditions (Persson and Höglind, 2014), an issue that was not taken in the simulations by Tao et al. (2015) due to lack of empirical data on this issue from the target region.

Output prices are a strong driver in the future as well. If output prices decrease, it is possible that in the future climate input use could be as low as it is in the current climate or even lower. Depending on the climate scenario, oat or set-aside would increase its area if lower prices would be realised. On the other hand, a price increase would encourage a typical farmer to produce more crops with high yield potentials, also considering input use (liming, fungicides etc.) effects on yields. As prices increase, spring wheat would take also area from barley, but barley would lose its position as a dominant crop in the area only if output prices increase very significantly compared to the input prices.

Potential threats related to SI in the future climate that arose in our study is the increasing use of fungicides and spring cereals monocultures. Monocultures combined with climate change may imply increasing disease and pest pressure, which could lead to increasing use of pesticides. There might therefore be need to set stronger restrictions for pesticide use in the future.

5. Conclusion

As we have shown, cereal farms in the North Savo region could benefit from higher yielding cultivars under climate change very significantly. 20–30% higher yields could increase the gross margin of a farm 42–52% compared to current levels, and significant gains could be realised even at low prices. Higher yields or crop prices could incentivise increased use of inputs such as liming and fungicide and further increase crop yields. Increased production would imply higher GHG emissions. Still, greenhouse emissions per unit of production are likely to decrease significantly from current levels. Our results suggest that increasing yield potential could encourage risk-averse farmers to increase the production of spring wheat. This is produced in the North Savo region only to a small extent in the present climate, due to low yields and high uncertainty. Barley would also increase its area significantly. Oat, which is relatively favourable in the area in the current climate due to its low costs and stable gross margin, is likely to be produced less in the future. There is also a strong demand in the region for barley grown for feed. Overall, the land use, input use, crop yields and gross margins per farm at North Savo will develop much in the direction of current cereals farms in southern Finland, with 20–30% higher yields and gross margins, and dominance of spring cereals in land use.

Nevertheless, market price developments and local demand largely determine other crops in cultivation. Higher yields or prices increase economic viability of all crops but do not automatically imply more diverse land use. O7ur results suggest that in the future climate there is a tendency towards spring barley and spring wheat dominance in the land use if higher crop yields or prices. Dominance of physiologically similar crops is a challenge for crop protection. Oilseeds cultivation, which is more risky than cereals cultivation currently in the region, would slightly benefit from increased crop prices. If output prices decrease, it is more likely that oat and set-aside, somewhat incentivised by current and recent agri-environmental programmes, could serve as alternative "break-crops" for spring barley and spring wheat.

Our results and findings are based on our method of integrating yield potentials of more adapted cultivars with yield responses resulting from the use of multiple inputs and dynamic land use effects. The results suggest that the use of inputs should be brought to the forefront if aiming for sustainable intensification. To what extent the use of inputs and spring cereals monocultures will be increased is a highly relevant issue for agriculture and society aiming for food security and sustainable development.

Our approach based on dynamic economic optimisation with multiple inputs and yield responses at the farm level is suitable at different farm types and situations. The model used could allow even more comprehensive analysis of farm level management and economy than done in this study. For example, we lack yield estimates and parameters concerning oilseeds and leguminous crops, and various pre-crop effects. Nutrient leaching into watercourses could provide more aspects related to sustainable intensification, if more data were available for the specification. The approach taken allows and requires further developments with applications to different farm types, regions and countries, to produce more results on economically rational adaptation at the farm level, including capital investments. Our approach provides a way to utilise bio-physical modelling results on climate change effects consistently in dynamic decision making on land use and input use at the farm level.

Appendix A. DEMCROP – formal description

A.1. Model description

I. Objective function

$$Max \sum_{t=1}^{30} \sum_{p}^{10} \sum_{i=1}^{M} \frac{1}{(1+r)^t} (Y(A(p,t,i),p,t,i)A(p,t,i)P(i) + S(i)$$

$$- C(p,t,i)) - \theta \sum_{t-1}^{H} \sum_{c} \sum_{c2} \frac{1}{(1+r)^t} A'XA \qquad (A.1)$$

subject to

$$\sum_{\forall i} A(p,t,i) = 1$$

II. Yield mean as response function of fertiliser

The mean crop yield levels can be expressed as functions of usage of nitrogen fertiliser N. Nitrogen fertilisation and the implied crop yield response are shown as Mitscherlich functions for barley, wheat and oat (*Avena sativa*) and quadratic functions for spring turnip rape (Lehtonen, 2001) as follows:

$$\begin{cases} Y_{mean}(N^i) = m(1 - ke^{bN^i}) & \text{when i = wheat, barley, oats} \\ Y_{mean}(N^i) = a_0 + b_0 N^i + c_0 N^{2i} & \text{when i=spring turnip rape} \end{cases} \tag{A.2}$$

III. Simulated yield function

$$Y\left(A(p,t,i) = \begin{cases} Y_{mean}(\cdot)Y_{RED}(p,t,i)((1 + L(p,t) + F(p,t,i) - \rho D(i)) & \text{if } i = \text{wheat or barley} \\ Y_{mean}(\cdot)Y_{RED}(p,t,i)((1 + L(p,t) & \text{if } i = \text{others} \end{cases}\right. \tag{A.3}$$

IV. Function of yield loss due to monoculture

$$Y_{RED}(p,t,i) = \sum_{\tau=1}^{5} \sum_{\forall c_2} A(p, t - \tau, i_2)(1 - T(i, i_2))^\tau \tag{A.4}$$

V. Response function of liming treatment

$$L(p,t) = \gamma_0 [pH(t - 1, p) - pH_{r0} - pH_{rN}(p,t,i) + \gamma_{ly} LM(p,t) - pH_{mean}] \tag{A.5}$$

VI. Response function of fungicide treatment

$$F(p,t,i) = \delta(p,t,i) \sum_{j=1}^{\gamma} \beta_j K_j(i) \tag{A.6}$$

VII. Disease loss function of wheat and barley

$$D(i) = \sum_{j}^{\gamma} K_j(i) \tag{A.7}$$

VIII. Cost function of farm management

$$C(p,t,i) = \begin{cases} C_{variable}(i) = C_{\log i}(p,t,i) + C_{fc}(p,t,i) + C_{\lim ing}(p,t) + C_{fer}(p,t,i) & \text{if } i = \text{wheat or barley} \\ C_{variable}(i) = C_{\log i}(p,t,i) + C_{\lim ing}(p,t) + C_{fer}(p,t,i) & \text{if } i = \text{others} \end{cases} \tag{A.8}$$

A.2. Description of notations corresponding to equations.

Equations	Notation	Definition
(A.1)	r	Discount rate
	p	Parcels
	i	Crops
	t	Years
	$Y(A(p,t,i),$ $p,t,i)$	Yield function of a crop i on an equally sized parcel p at year t
	$A(p,t,i)$	A variable describing allocation of land parcel p for a crop i at the year t
	$P(i)$	The vector of expected prices of crops i, €/kg
	$S(i)$	Subsidies for each crop i, €/ha
	$C(p,t,i)$	Cost function for cultivating a crop i at a parcel p at year t
	θ	Risk aversion coefficient
	X	is a covariance matrix of gross margins of the crops, assumed unchanged from 1995 to 2015 period
(A.2)	$Y_{MEAN}(p,i)$	Mean yield of the crop i on a parcel p.
	N^i	nitrogen fertiliser for crop i
	$m, k, b,$ a_0, b_0, c_0	Parameters used for each i crop
(A.3)	$Y_{RED}(p,t,i)$	Transformation function of a yield loss matrix due to monoculture
	$L(p,t)$	Response function of liming treatment at the time t for parcel p
	$F(p,t,i)$	Response function of fungicide treatment for crop i at the year t on parcel p
	$D(i)$	Yield loss percentage caused by diseases for crop i
(A.4)	$T(i,i_2)$	Transition matrix, which describes a fraction of the yield lost due to monoculture. $0 < T(i,i_2) < 1$
	τ	Parameter of carry over effect of yield loss in years due to monoculture, which is set to be 5.

(A.5)	γ_0	Yield response coefficient of pH value, i.e. yield margin percentage due to 1 unit change of pH value in soil.
	$pH(t-1, p)$	The soil pH values on the parcel p at the time $t–1$
	pH_{r0}	Constant annual reduction of pH value, independent of the nitrogen fertilisation, whereas the level of nitrogen fertilisation also results in decreasing pH value of the soil
	$pH_r(p,t,i)$	Yield reduction function of pH value on the parcel p at the time t for crop i
	γ	Constant coefficient of lime efficiency, i.e. the increase of pH when 1 ton per hectare of lime is spread
	$LM(t, p)$	Lime amount used at the parcel p at the time t.
	pH_{mean}	Constant value describing the mean pH value at farm
(A.6-A.7)	$\delta(p,t,i)$	Dummy variable, whose value equals 1 when fungicide treatment is given to the crop i = barley j = wheat on a parcel p at the time t, otherwise equals 0.
	β_j	Efficiency coefficient of fungicide treatment corresponding to yield loss of j types of diseases
	K_j	Percentage of yield losses in correspondence to the j types of diseases for crop i = barley and wheat
(A.8)	$C_{variable}(i)$	Vector variable cost of the crop i
	$C_{fc}(i)$	Sum cost of fungicide substance and labour cost of spreading fungicide for barley and wheat for crop i
	$C_{\log i}(p,t,i)$	Function of logistics costs of crop i on a parcel p in year t
	$C_{\lim ing}(p,t)$	Quadratic cost function of using liming adaptation on a parcel p at year t
	$C_{fer}(p,t,i)$	Linear cost function of fertiliser usage

References

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P.J., Rötter, R.P., Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P.K., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A.J., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J.E., Osborne, T.M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M.A., Shcherbak, I., Steduto, P., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., Wallach, D., White, J.W., Williams, J.R., Wolf, J., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Chang. 3 (9), 827–832.

Bindi, M., Olesen, J., 2011. The responses of agriculture in Europe to climate change. Reg. Environ. Chang. 11, 151–158.

Blanco, M., Ramos, F., van Doorslaer, B., Martínez, P., Fumagalli, D., Ceglarb, A., Fernández, J.I., 2017. Climate change impacts on EU agriculture: a regionalized perspective taking into account market-driven adjustments. Agric. Syst. 156 (2017), 52–66.

Dono, G., Cortignani, R.,, D., Deligios, P., Doro, L., Lacetera, N., Mula, L., Pasqui, M., Quaresima, S., Vitali, A., Roggero, P.P., 2016. Winners and losers from climate change in agriculture: insights from a case study in the Mediterranean basin. Agric. Syst., 147, 66–75.

FAO, IFAD, IMF, OECD, UNCTAD, WFP, the World Bank, the WTO, IFPRI, UN HLTF, 2011. Price Volatility in Food and Agricultural Markets: Policy Responses. Food and Agricultural Organization.

Hiironen, J., Ettanen, S., 2013. Peltoalueiden tilusrakenne ja sen parantamismahdollisuudet. Maanmittauslaitoksen julkaisuja no. 113.

Höglind, M., Thorsen, S.M., Semenov, M.A., 2013. Assessing uncertainties in impact of climate change on grass production in Northern Europe using ensembles of global climate models. Agric. For. Meteorol. 170, 103–113.

Huttunen, I., Lehtonen, H., Huttunen, M., Piirainen, V., Korppoo, M., Veijalainen, N., Viitasalo, M., Vehviläinen, B., 2015. Effects of climate change and agricultural adaptation on nutrient loading from Finnish catchments to the Baltic Sea. Sci. Total Environ. 529, 168–181. http://dx.doi.org/10.1016/j.scitotenv.2015.05.055.

IPCC, 2014. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 688.

Lehtonen, H., 2001. Principles, Structure and Application of Dynamic Regional Sector Model of Finnish Agriculture. Academic dissertation. Systems Analysis Laboratory, Helsinki University of Technology. Publications 98. Agrifood Research Finland, Economic Research (MTTL), Helsinki.

Lehtonen, H., 2012. Sector-level economic modeling as a tool in evaluating greenhouse gas mitigation options. Acta. Agric. Scand. 62 (4), 326–335. http://dx.doi.org/10.1080/09064702.2013.797011.

Lehtonen, H., 2015. Evaluating adaptation and the production development of Finnish agriculture in climate and global change. Agric. Food Sci. 24, 219–234. http://ojs.tsv.fi/index.php/AFS/article/view/51080.

Lehtonen, H., Liu, X., Purola, T., 2016a. Balancing climate change mitigation and adaptation with socio-economic goals at farms in northern Europe. In: Paloviita, A., Järvelä, M. (Eds.), Climate Change Adaptation and Food Supply Chain Management (Routledge Advances in Climate Change Research). Routledge, London, pp. 132–146. ISBN13: 978-1138796669. http://www.tandf.net/books/details/9781317634034/.

Lehtonen, I., Kämäräinen, M., Gregow, H., Venäläinen, A., Peltola, H., 2016b. Heavy snow loads in Finnish forests respond regionally asymmetrically to projected climate change. Nat. Hazards Earth Syst. Sci. 16, 2259–2271. http://dx.doi.org/10.5194/nhess-16-2259-2016.

Liu, X., Lehtonen, H., Purola, T., Pavlova, Y., Rötter, R., Palosuo, T., 2016. Dynamic economic modelling of crop rotations with farm management practices under future pest pressure. Agric. Syst. 144, 65–76. http://dx.doi.org/10.1016/j.agsy.2015.12.003.

Luke, 2017a. Income Statement. Luke Profitability Bookkeeping Results. December 15, 2017. https://portal.mtt.fi/portal/page/portal/economydoctor/farm_economy/timeline/income_statement.

Luke, 2017b. Yield of the Main Crops 1999–2015. North Savo ELY Centre. Luke Natural Resources Institute Finland.

Luke, 2017c. Producer Prices of Agricultural Products. Luke Natural Resources Institute Finland. http://stat.luke.fi/en/producer-prices-of-agricultural-products.

Mäenpää, A., 2010. Plant Disease Forecasting Model, Needs and Usefulness. Bachelor's thesis. HAMK University of Applied Sciences. Degree Programme in Agricultural and Rural Industries. https://publications.theseus.fi/bitstream/handle/10024/13163/korjattu%20oppari%20valmis%20aleksi_1.pdf.

Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J., Taylor, K.E., 2007. The WCRP CMIP3 multimodel dataset - a new era in climate change research. Bull. Am. Meteorol. Soc. 88, 1383–1394. http://dx.doi.org/10.1175/BAMS-88-9-1383.

Mittenzwei, K., Persson, T., Höglind, M., Kværnø, S., 2017. Combined effects of climate change and policy uncertainty on the agricultural sector in Norway. Agric. Syst. 153, 118–126.

Moschini, G., Hennessy, D.A., 2001. Uncertainty, Risk Aversion, and Risk Management for Agricultural Producers. In: Gardner, B., Rausser, G. (Eds.), Handbook in Agricultural Economics. vol 1a. Elsevier Science, Amsterdam, pp. 87–153.

Myyrä, S., Ketoja, E., Yli-Halla, M., Pietola, K., 2005. Land improvements under land tenure insecurity: the case of pH and phosphate in Finland. Land Econ. 81 (4), 557–569.

Nakicenovic, N., Alcamo, J., Davis, G., Davis, J., de Fries, G., Fenhann, B., Gaffin, J., Gregory, S., Grubler, K., Jung, A., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Raihi, K., Roehrl, A., Rogner, H.H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., von Rooijen, S., Victor, N., Dadi, Z., 2000. Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Nelson, G.C., Valin, H., Sands, R.D., Havlik, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., Von Lampe, M., Lotze-Campen, H., Mason D'croz, D., Van Meijl, H., Van Der Mensbrugghe, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Müller, C., Tabeau, A., Willenbockel, D., 2014. Climate change effects on agriculture: economic responses to biophysical shocks. Proc. Natl. Acad. Sci. U. S. A. 111 (9), 3274–3279.

Özkan, G.S., Aspeholen, Å.B., Persson, T., Höglind, M., Mittenzwei, K., 2017. Combining models to estimate the impacts of future climate scenarios on feed supply, greenhouse gas emissions and economic performance on dairy farms in Norway. Agric. Syst. 157 (2017), 157–169.

Palosuo, T., Rötter, R.P., Salo, T., Peltonen-Sainio, P., Tao, F., Lehtonen, H., 2015. Effects of climate and historical adaptation measures on barley yield trends in Finland. Clim. Res. 65, 221–236. http://dx.doi.org/10.3354/cr01317.

Peltonen-Sainio, P., Jauhiainen, L., Hannukkala, A., 2007. Declining rapeseed yields in Finland: how, why and what next? The. J. Agric. Sci. 145, 587–598.

Peltonen-Sainio, P., Jauhiainen, L., Hakala, K., Ojanen, H., 2009. Climate change and prolongation of growing season: changes in regional potential for field crop production in Finland. Agric. Food Sci. 18, 171–190.

Peltonen-Sainio, P., Salo, T., Jauhiainen, L., Lehtonen, H., Sieviläinen, E., 2015. Static Yields and Quality Issues: Is the Agri-environmental Program the Primary Driver? AMBIO. ISSN 0044-7447. http://dx.doi.org/10.1007/s13280-015-0637-9.

Persson, T., Höglind, M., 2014. Impact of climate change on harvest security and biomass yield of two timothy ley harvesting systems in Norway. J. Agric. Sci. 152, 205–216. http://dx.doi.org/10.1017/S0021859612001013.

Purola, T., 2013. Taudinkestävien ja tautialttiiden ohralajikkeiden taloudellinen vertailu. Master thesis. University of Helsinki. Department of economics and management.

https://helda.helsinki.fi/handle/10138/40225.

Rogelj, J., Meinshausen, M., Knutti, R., 2012. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. Nat. Clim. Chang. 2, 248–253. http://dx.doi.org/10.1038/NCLIMATE1385.

Rötter, R.P., Höhn, J.G., Fronzek, S., 2012. Projections of climate change impacts on crop production: a global and a Nordic perspective. Acta. Agric. Scand. A 62, 166–180.

Rötter, R.P., Höhn, J., Trnka, M., Fronzek, S., Carter, T.R., Kahiluoto, H., 2013. Modelling shifts in agroclimate and crop cultivar response under climate change. Ecol. Evol. 3, 4197–4214.

Ruosteenoja, K., Räisänen, J., Pirinen, P., 2011. Projected changes in thermal seasons and the growing season in Finland. Int. J. Climatol. 31, 1473–1487.

Ruosteenoja, K., Räisänen, J., Venäläinen, A., Kämäräinen, M., 2016. Projections for the duration and degree days of the thermal growing season in Europe derived from CMIP5 model output. Int. J. Climatol. 36, 3039–3055. http://dx.doi.org/10.1002/joc.4535.

Schönhart, M., Schauppenlehner, T., Kuttner, M., Kirchner, M., Schmid, E., 2016. Climate change impacts on farm production, landscape appearance, and the environment: policy scenario results from an integrated field-farm-landscape model in Austria. Agric. Syst. 145, 39–50.

Seppälä, A., Kässi, P., Lehtonen, H., Aro-Heinilä, E., Niemeläinen, O., Lehtonen, E., Höhn, J., Salo, T., Keskitalo, M., Nysand, M., Winquist, E., Luostarinen, S., Paavola, T., 2014. Nurmesta biokaasua liikennepolttoaineeksi. Bionurmi-hankkeen loppuraportti. MTT Reports:151. http://urn.fi/URN:ISBN:978-952-487-546-2.

Shipton, P., 1977. Monoculture and soilborne plant pathogens. Annu. Rev. Phytopathol. 15, 387–407.

Statistics Finland, 2017. Official Statistics of Finland (OSF): Index of Purchase Prices of the Means of Agricultural Production. http://www.stat.fi/til/ttohi/index_en.html.

Tao, F., Zhang, Z., 2013. Climate change, wheat productivity and water use in the North China Plain: a new super-ensemble-based probabilistic projection. Agric. For. Meteorol. 170, 146–166.

Tao, F., Yokozawa, M., Zhang, Z., 2009. Modeling the impacts of weather and climate variability on crop productivity over a large area: a new process-based model development, optimization, and uncertainties analysis. Agric. For. Meteorol. 149, 831–850.

Tao, F., Rötter, R.P., Palosuo, T., Höhn, J., Peltonen-Sainio, P., Rajala, A., Salo, T., 2015. Assessing climate impacts on wheat yield and water use in Finland using a super-ensemble-based probabilistic approach. Clim. Res. 65, 23–37.

Tike, 1996–1999. Yearbook of Farm Statistics. Official statistics of Finland.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Nat. Acad. Sci. USA. 108, 20260–20264. http://dx.doi.org/10.1073/pnas.1116437108.

Viljavuuspalvelu, 2017. Pintamaan maalajisuhteet maaseutukeskuksen ProAgria Pohjois-Savo alueella 2006–2010.

van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.M., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., Winkler, H., 2014. A new scenario framework for climate change research: scenario matrix architecture. Clim. Chang. 122 (3), 373–386.

Zessner, M., Schönhart, M., Parajka, J., Trautvetter, H., Mitter, H., Kirchner, M., Hepp, G., Blaschke, A.P., Strenn, B., Schmid, E., 2017. Sci. Total Environ. 579, 1137–1151.

Zimmermann, A., Webber, H., Zhaob, G., Ewert, F., Kros, J., Wolf, J., Britz, W., de Vries, W., 2017. Climate change impacts on crop yields, land use and environment in response to crop sowing dates and thermal time requirements. Agric. Syst. 157 (2017), 81–92.